New Color-Octet Vector Boson?

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Both CDF and D0 at Tevatron reported the measurements of forward-backward asymmetry in top pair production, which showed possible deviation from the standard model QCD prediction. In this paper, we show that a new color-octet massive vector boson with mass just above twice that of top quark can simultaneously account for the asymmetry and differential distribution $d\sigma/dM_{t\bar{t}}$ in top pair production, without conflict with other measurements for example di-jet production. The new particle can be discovered and studied at the more powerful Large Hadron Collider.

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Discovering new particle is one of the most important goals for higher and higher energy colliders, such as Tevatron at Fermilab and Large Hadron Collider (LHC) at CERN. Top quark was discovered in 1995 at Tevatron. Since the important discovery, measuring properties of top quark is one of the most active field in high energy physics. The endeavor is justified because the top quark is the heaviest ever known fermion and is thought to be related to mechanism of electro-weak symmetry breaking and physics beyond the standard model (SM). Most of measured properties such as mass, width, production rate are consistent with SM predictions, however the CDF and D0 Collaboration have observed possible deviation on forward-backward (FB) asymmetry in top quark pair production. In this paper we will show that the deviation can be due to the new color-octet massive vector boson.

At $t\bar{t}$ frame the FB asymmetry in top quark pair production A_{FB} is defined as

$$A_{FB} = \frac{\sigma(\Delta Y>0)-\sigma(\Delta Y<0)}{\sigma(\Delta Y>0)+\sigma(\Delta Y<0)} \equiv \frac{\sigma_A}{\sigma}, \qquad (1)$$

where $\Delta Y \equiv Y_t - Y_{\bar{t}}$ is the difference between rapidity of the top and anti-top quark, which is invariant under $t\bar{t}$ or $p\bar{p}$ rest frame.

The measurements of CDF and D0 are [1, 2],

$$\begin{aligned} A_{FB}^{CDF} &= 0.158 \pm 0.072 \pm 0.017, \text{with } 5.3 fb^{-1}; \\ A_{FB}^{D0} &= 0.08 \pm 0.04 \pm 0.01, \text{with } 4.3 fb^{-1}. \end{aligned} \qquad (2)$$

The measurements are consistent with previous ones [3–5], but reveal about a 2σ deviation from the SM's prediction [6–11]. The discrepancy has inspired lots of new physics discussions [12–21]. These discussions can be roughly classified into two categories. One category is by introducing a Z' or W' which have flavor changing couplings with fermions. The flavor changing coupling among Z', top and up quarks can induce a t-channel diagram of $u\bar{u} \to t\bar{t}$ which contributes to A_{FB} via the interference with usual QCD tree diagrams. The other category is by introducing a heavy(> 1TeV) axial-gluon. It induces a s-channel diagram of $q\bar{q} \to t\bar{t}$ which contributes to A_{FB} via the interference with usual QCD tree diagrams and/or itself. However, for the new physics in the first category, $d\sigma/dM_{t\bar{t}}$ distribution for top pair production is violated greatly [14], even after including more higher-order effects [22]. Other severe constraint comes from the measurement of same-sign top production rate at Tevatron [14, 23]. For the second category of new physics, the suitable parameters to account for all existing measurements can hardly be found [12, 24], especially to satisfy the constraint from the high $M_{t\bar{t}}$ region. The lesson from these investigations [12–21] is that it is very difficult to account for A_{FB} without distorting the shape of $d\sigma/dM_{t\bar{t}}$. Totally new idea is indispensable. How about to introduce *s-channel* diagram induced by a *low mass* color-octet vector boson? In this case, the A_{FB} can be induced by interference with the corresponding QCD diagrams, at the same time the shape of $d\sigma/dM_{t\bar{t}}$ for high $M_{t\bar{t}}$ is minimally affected. In this paper we will show that by introducing a new color-octet massive vector boson (denoted by Z_C hereafter) with the mass M_C just above $2m_t$, the measured A_{FB} and $d\sigma/dM_{t\bar{t}}$ can be accounted for. Furthermore such kind of new particle are compatible with all other measurements.

In Fig. 1, the measurements [25] and predictions in the SM for A_{FB} and $d\sigma/dM_{t\bar{t}}$ are depicted. From the figures it is quite natural to expect that extra contributions to *both* A_{FB} and $d\sigma/dM_{t\bar{t}}$ are in the low $M_{t\bar{t}}$ region. Adopting the central values, the extra asymmetric cross section $\delta\sigma_A$ of ~ 800 fb is required. At the same time additional ~ 700 fb

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cross section $\delta\sigma$ is also required in the 350-400 GeV bin, which is hardly accommodated by threshold resummation [9, 11]. The resummation effects will increase the distribution evenly over the whole $M_{t\bar{t}}$ region.

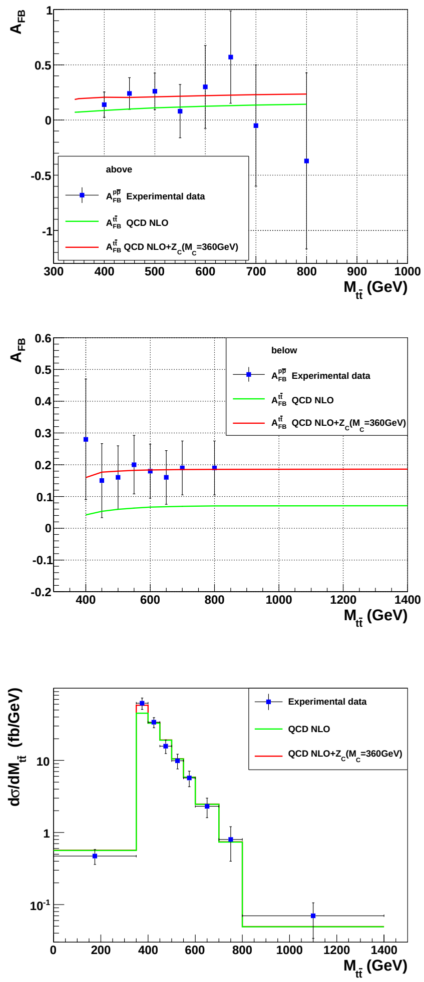

FIG. 1: A_{FB} and $d\sigma/dM_{t\bar{t}}$ as a function of $M_{t\bar{t}}$ in the SM and Z_C+SM. For the new particle Z_C, $M_C = 360$GeV is chosen. Other allowed M_C induces the similar behavior. Experimental data is also shown. Here 'above' and 'below' represent that A_{FB} is calculated above or below a specific $M_{t\bar{t}}$ and $m_t = 170.9$ GeV.

Color-octet massive particle conjectured in physics beyond the SM (BSM) is nothing new. For example in supersymmetric models there is gluino, namely the supersymmetric partner of gluon. Gluinos couple with the color particle in the strength of strong interaction which is well described by QCD. Another example is the above-mentioned axial-gluon which is the mediator for the new gauge group. Such axigluon has been proposed to account for the FB asymmetry in top pair production with the mass of axial-gluon at $\mathcal{O}(1)$ TeV. However imposing the constraints from differential distribution of top pair invariant mass, dijet production measurement, as well as other low energy measurements, such proposals seem to be disfavored. The failure to account for FB asymmetry in top pair production utilizing axial-gluon lies in the implicit assumption of the couplings with top quark and light quarks, which are at $\mathcal{O}(g_S)$ i.e. the strong coupling constant.

In the phenomenological model we introduce a new color-octet axial massive vector boson Z_C. The coupling with the top-quark is taken to be $-ig_t\gamma^\mu\gamma^5T^a$, and coupling with other quarks to be $-ig_q\gamma^\mu\gamma^5T^a$ [1].

In this model, $\delta\sigma_A$ arises from the left diagram and $\delta\sigma$ the right one in Fig. 2. The analytical expression of $\sum_{\text{Color,Spin}}|M|^2$ for the left diagram can be written as

$$32\pi C_A C_F \alpha_s g_q g_t \frac{(s-M_C^2)s}{(s-M_C^2)^2+\Gamma_C^2 M_C^2}\cos\theta\beta, \quad (3)$$

where $C_A = 3$, $C_F = 4/3$, $\beta \equiv \sqrt{1-4m_t/s}$ and Γ_C is the total width of Z_C

$$\Gamma_C = \sum_i^{2m_i<M_C} \frac{g_i^2}{4\pi}\frac{C_F}{8}(1-4m_i^2/M_C^2)^{\frac{3}{2}}M_C.$$

$\sum_{\text{Color,Spin}}|M|^2$ for the right diagram can be written as

$$2C_A C_F (g_q g_t)^2 \frac{s^2}{(s-M_C^2)^2+\Gamma_C^2 M_C^2}(1+\cos^2\theta)\beta^2. \quad (4)$$

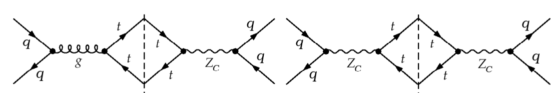

FIG. 2: Left diagram: interference between usual QCD tree diagram and Z_C induced tree diagram. Right diagram: square of Z_C induced tree diagram.

In the following we will determine the model parameters namely M_C and the two couplings constants g_t and g_q, utilizing the $\delta\sigma_A = 800$ fb and $\delta\sigma = 700$ fb. The procedure is divided into two steps.

Step one: Determining the parameters using $\delta\sigma_A$ and $\delta\sigma$. There are three additional free parameters M_C, g_t, g_q. For the convenience of numerical analysis, we first transform the three free

[1] In the realistic model, bottom quark is usually grouped with top quark. The assumption here does not change our main results.

parameters into M_C, $g_t g_q$ and g_q/g_t. All possible g_q/g_t, M_C and $g_t g_q$ can be found by scanning the parameter space.

Step two: Limiting the parameters g_q/g_t, M_C and $g_t g_q$ by requiring that the extra contribution from Z_C can improve the agreement between theoretical predictions and experimental measurements, namely the distributions of $d\sigma/dM_{t\bar{t}}$ and A_{FB}. The possible parameter g_q/g_t is confined to a very narrow region $0.0040 \le g_q/g_t \le 0.0044$. At the same time, M_C and $g_t g_q$ are approximately written as

$$g_q g_t \simeq 0.2\frac{M_C - 290[GeV]}{m_t}; 350\,\text{GeV} \le M_C \le 380\,\text{GeV}.$$

In Fig. 1 we show the excellent agreement between theoretical predictions and data after including extra contributions from Z_C with the possible parameter set $M_C = 360$ GeV, $g_q/g_t = 0.0042$ and $g_q g_t = 0.082$. As for g_q, extra constraint may arise from the measurements of di-jet production [26]. However it is obviously that the required g_q here is much less than the limit.

We should emphasize that the numerical results here is just for the illustration purpose. The generic features for other allowed $\delta\sigma_A$ and $\delta\sigma$ due to the uncertainties of measurements are the same, namely (1) color octet vector boson with mass just above $2m_t$ can improve the agreement between the predictions and data; (2) the coupling among new vector boson with top is much larger than that of light quarks; (3) the couplings of Z_C should be axial-vector like. The third point can be understood as following. If taking the more generic coupling of Z_C as $(g_V\gamma^\mu + g_A\gamma^\mu\gamma^5)$ in the beginning, we find that g_V has to be much smaller than g_A in order to account for $\delta\sigma$ and $\delta\sigma_A$ simultaneously. The underlying reason is very simple. The $\sum |M|^2$ of $\delta\sigma_A$ brought by g_A is proportional to β (cf. Eq. 3), while the $\sum |M|^2$ of $\delta\sigma$ brought by g_V doesn't have this feature. For $M_{t\bar{t}}$ in 350-400 GeV, β is small, therefor g_V has to be much smaller than g_A in order not to bring much more $\delta\sigma$ than $\delta\sigma_A$. It is the observed $\delta\sigma$ and $\delta\sigma_A$ that fix the coupling g_V much less than g_A.

The key difference between the proposed model and the axial-gluon model introduced in Ref. [12] is that, for the latter the mass of axial-gluon is quite heavy ($\mathscr{O}(1)$TeV) so the the axial couplings with top and other quarks have the *opposite* sign in order to induce the positive A_{FB} from interference, while in this model, the M_C is assumed just above $2m_t$ and the axial-vector couplings with top-quark and the other quarks have the *same* sign.

Tevatron has shown sign of the new color-octet vector boson, and it is quite natural to explore how to discover and study such kind of new particle at the more powerful LHC. In Fig. 3, we show the differential cross section $d\sigma/dM_{t\bar{t}}$ as a function of $M_{t\bar{t}}$ in Z_C model. It is clear that the top-antitop production cross section is larger than that of in the SM, especially in the low $M_{t\bar{t}}$ region via the sub-process $q\bar{q} \to t\bar{t}$ at LHC. Due to the Yang theorem, on-shell Z_C does not contribute to top pair production in gluon-gluon fusion, which is the main production mechanism in the SM. The bump of Z_C at $M_{t\bar{t}}$ should appear after collecting enough data samples.

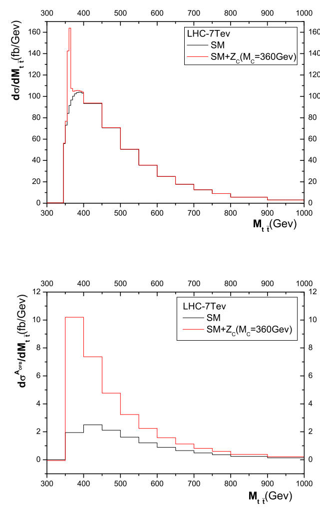

FIG. 3: Differential cross section $d\sigma/dM_{t\bar{t}}$ (up figure) and differential one-side asymmetric cross section $d\sigma^{A_{\rm OFB}}/dM_{t\bar{t}}$ (bottom figure) in Z_C+SM and SM. Here $M_C = 360$GeV is chosen, and the other allowed M_C give the similar behavior. Note that $P^z_{t\bar{t},\rm cut}$, namely the top pair momentum cut in z-direction, is used for σ and $\sigma^{A_{\rm OFB}}$ calculations.

The coupling properties of new particle can be studied via the angular distributions. However the usual forward-backward asymmetry defined at Tevatron is not applicable at LHC. The reason is that LHC is the proton-proton collider, there is no preferred direction which is contrary to the proton anti-proton colldier Tevaton. Fortunately, there are some solutions [6–8, 27, 28]. Based on Ref. [28] we will study the one-side forward-backward asymmetry in the Z_C model. The differential one-side asymmetric cross-section $d\sigma^{A_{\rm OFB}}/dM_{t\bar{t}}$ is shown in Fig. 3, which is important to distinguish Z_C model from other possible contributions. The integrated one-side asymmetric cross sections $\sigma^{A_{\rm OFB}}$ are depicted in Tab. 1. Also shown is the signal significance Sig which is defined as

$$Sig = \frac{\sigma^{A_{\rm OFB}}_{{\rm SM}+Z_C} - \sigma^{A_{\rm OFB}}_{\rm SM}}{\sqrt{\sigma_{\rm SM}}}\sqrt{\mathscr{L}},$$

where $\mathscr{L}$ is taken to be 10fb^{-1}. In order to beat the huge QCD backgrounds, especially the ones

from gluon-gluon fusion, selection cuts are necessary both for σ and for $\sigma^{A_{\rm OFB}}$[28]. The optimal choice of cuts is $P^z_{t\bar{t},{\rm cut}} = 600$GeV for LHC at 7 TeV and $P^z_{t\bar{t},{\rm cut}} = 1.2$TeV for LHC at 14 TeV [28]. From the figure and table, LHC can discover and measure the coupling nature of such kind of Z_C with quite low integrated luminosity.

TABLE I: Total one-side asymmetric cross section (fb) in Z_C+SM. In the SM, $\sigma_{\rm SM(LO)} \simeq 22.2\times10^3$, 75×10^3fb and $\sigma^{A_{\rm OFB}}_{\rm SM} \simeq 650$, 1650fb for $\sqrt{s} = 7$ and 14 TeV respectively. Note that $P^z_{t\bar{t},{\rm cut}}$ is used for all the σ and $\sigma^{A_{\rm OFB}}$ calculations.

	$\sigma^{A_{\rm OFB}}_{{\rm SM}+Z_C}(M_C=)$			$Sig(M_C=)$		
	355.0	360.0	370.0	355.0	360.0	370.0
7 TeV	1623	1670	1716	20.63	21.62	22.61
14 TeV	3971	4096	4245	26.69	28.13	29.85

To summarize, both CDF and D0 at Tevatron reported the measurements of forward-backward asymmetry in top pair production. Theoretically such asymmetry is due to the higher-order QCD processes in the SM. The measurements showed possible deviation from the theoretical prediction. In this paper a phenomenological model which contains the new color-octet massive vector boson Z_C is proposed. When the mass of Z_C is just above twice that of top quark and the couplings are appropriately chosen, the asymmetry and distribution of $M_{t\bar{t}}$ in top pair production can be explained simultaneously, without conflict with other measurements for example di-jet production.

We would like to emphasize the implications of our study for model-building. The requirements for the new massive color-octet vector boson Z_C are (1) M_C is just above $2m_t$; (2) the nature of couplings among Z_C and quarks is axial-vector like; (3) the axial coupling of Z_C with top quark is much larger than that with light quarks, but are of the same sign, which is contrary to the conventional axial-gluon models. These features indicate that Z_C can be intimately correlated with conjectured top quark pair condensate, and even the mechanism of electro-weak symmetry breaking. We are not aware of any models in literature which have such features. Hopefully the Tevatron asymmetry measurements are the sign for the new particle and true underlying mechanism will be uncovered at the LHC.

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[1] M. Tecchio *et al.*, CDFnote 10224.
[2] V. Shary (on behalf of D0), talk given at ICHEP2010, Paris.
[3] D0, V. M. Abazov *et al.*, Phys. Rev. Lett. **100**, 142002 (2008), 0712.0851.
[4] CDF, T. Aaltonen *et al.*, Phys. Rev. Lett. **101**, 202001 (2008), 0806.2472.
[5] CDF, T. Aaltonen *et al.*, Phys. Rev. Lett. **102**, 222003 (2009), 0903.2850.
[6] J. H. Kühn and G. Rodrigo, Phys. Rev. Lett. **81**, 49 (1998).
[7] J. H. Kuhn and G. Rodrigo, Phys. Rev. **D59**, 054017 (1999), hep-ph/9807420.
[8] O. Antuñano, J. H. Kühn, and G. Rodrigo, Phys. Rev. D **77**, 014003 (2008).
[9] L. G. Almeida, G. Sterman, and W. Vogelsang, Phys. Rev. D **78**, 014008 (2008).
[10] W. Bernreuther and Z.-G. Si, Nucl. Phys. **B837**, 90 (2010), 1003.3926.
[11] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, (2010), 1003.5827.
[12] P. H. Frampton, J. Shu, and K. Wang, Phys. Lett. **B683**, 294 (2010), 0911.2955.
[13] J. Shu, T. M. P. Tait, and K. Wang, Phys. Rev. **D81**, 034012 (2010), 0911.3237.
[14] S. Jung, H. Murayama, A. Pierce, and J. D. Wells, Phys. Rev. **D81**, 015004 (2010), 0907.4112.
[15] K. Cheung, W.-Y. Keung, and T.-C. Yuan, Phys. Lett. **B682**, 287 (2009), 0908.2589.
[16] Q.-H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, and C. E. M. Wagner, (2010), 1003.3461.
[17] A. Djouadi, G. Moreau, F. Richard, and R. K. Singh, (2009), 0906.0604.
[18] D.-W. Jung, P. Ko, J. S. Lee, and S.-h. Nam, Phys. Lett. **B691**, 238 (2010), 0912.1105.
[19] J. Cao, Z. Heng, L. Wu, and J. M. Yang, Phys. Rev. D **81**, 014016 (2010).
[20] V. Barger, W.-Y. Keung, and C.-T. Yu, Phys. Rev. D **81**, 113009 (2010).
[21] A. Arhrib, R. Benbrik, and C.-H. Chen, (2009), 0911.4875.
[22] B. Xiao, Y.-k. Wang, and S.-h. Zhu, Phys. Rev. **D82**, 034026 (2010), 1006.2510.
[23] CDF, T. Aaltonen *et al.*, Phys. Rev. Lett. **102**, 041801 (2009), 0809.4903.
[24] R. S. Chivukula, E. H. Simmons, and C. P. Yuan, (2010), 1007.0260.
[25] M. Tecchio *et al.*, "Measurement of the dependence of the forward-backward asymmetry in top pair production on mtt", CDFnote 9724.
[26] CDF, T. Aaltonen *et al.*, Phys. Rev. **D79**, 112002 (2009), 0812.4036.
[27] P. Ferrario and G. Rodrigo, Phys. Rev. **D78**, 094018 (2008), 0809.3354.
[28] Y.-k. Wang, B. Xiao, and S.-h. Zhu, (2010), 1008.2685 (in press).